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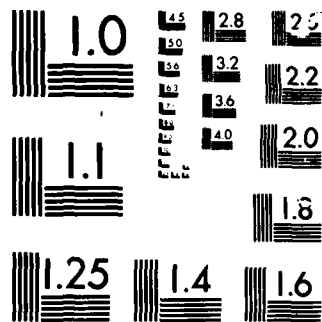
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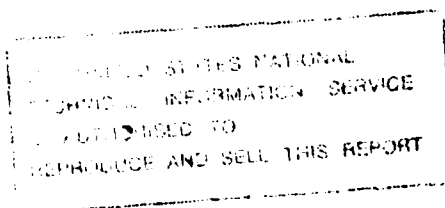
DEPARTMENT OF DEFENCE
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REPORT

MRL-R-980

WAVE SHAPING IN THE MRL 38 MM SHAPED CHARGE

D.A. Jones



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ABSTRACT

The effect of wave shaping on the MRL 38 mm shaped charge is considered. A simple extension of the Pugh, Eichelberg and Rostoker theory is used to consider the effect of both spherically diverging and spherically converging detonation waves on jet performance, and then a more sophisticated analytical approach is used to look at the expected increase in jet-tip velocity produced by a conical detonation wave. This predicted jet-tip velocity is compared with the result from a HELP-code simulation of the same event. Numerical problems occurred in the latter, but both methods predict a considerable increase in the velocity of the jet-tip. Some problems involved with the experimental formation of a conical detonation wave are then briefly discussed.

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DOCUMENT CONTROL DATA SHEET

REPORT NO. MRL-R-980	AR NO. AR-004-346	REPORT SECURITY CLASSIFICATION Unclassified
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TITLE

Wave shaping in the MRL 38 mm shaped charge

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REPORT DATE
December 1985

TASK NO.
DST 85/158

SPONSOR
DSTO

FILE NO.
G6/4/8-3087

REFERENCES
17

PAGES
18

CLASSIFICATION/LIMITATION REVIEW DATE

CLASSIFICATION/RELEASE AUTHORITY
Superintendent, MRL
Physical Chemistry Division

SECONDARY DISTRIBUTION

Approved for Public Release

ANNOUNCEMENT

Announcement of this report is unlimited

KEYWORDS

Shaped Charges

Wave shaping
Detonation waves
Jets

Simulation

COSATI GROUPS 1901

ABSTRACT

The effect of wave shaping on the MRL 38 mm shaped charge is considered. A simple extension of the Pugh, Eichelberg and Rostoker theory is used to consider the effect of both spherically diverging and spherically converging detonation waves on jet performance, and then a more sophisticated analytical approach is used to look at the expected increase in jet-tip velocity produced by a conical detonation wave. This predicted jet-tip velocity is compared with the result from a HELP-code simulation of the same event. Numerical problems occurred in the latter, but both methods predict a considerable increase in the velocity of the jet-tip. Some problems involved with the experimental formation of a conical detonation wave are then briefly discussed.

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GLOSSARY OF SYMBOLS

U_D	Velocity of detonation wave in cm/ μ s
V_O	Final collapse velocity of liner in cm/ μ s
α	Original cone half angle
β	Generic symbol for collapse angle
U	$U_D/\cos \alpha$, in cm/ μ s
δ	Taylor angle, the angle between the direction an element of the liner travels and the normal to its original position
V_j	Speed of jet, in cm/ μ s. This varies along the length of the jet
$V_j(\text{tip})$	Velocity of jet tip, cm/ μ s
m	Mass per unit length of liner, in g/cm
m_j	Mass per unit length of jet at stagnation point, in g/cm
m_s	Mass per unit length of slug at stagnation point, in g/cm
x	Measures distance along cone axis from apex, in cm
T	Time for detonation wave to travel distance x , in μ s
A	$\alpha + \delta$
V'_O	Derivative of V_O with respect to x , in (μ s) $^{-1}$
τ	Time constant for acceleration of liner, in μ s
l	Length coordinate along liner contour, in cm
γ	Minimum angle between the normal to the detonation wave front and the cone wall at their point of intersection
K, ϕ_O	Empirical constants used in the Richter approximation for δ
d	For a spherically diverging wave this represents the distance between the apex of the cone and the point of initiation. For a spherically converging wave it is the distance between the apex of the cone and the point to which the wave is converging. Measured in cm.

WAVE SHAPING IN THE MRL 38 MM SHAPED CHARGE

1. INTRODUCTION

There has recently been a resurgence of interest in the effect of wave-shaping on the performance of shaped charge weapons [1]. MRL also has an interest in this area because of the probable use by the Australian Army of the 103 mm MILAN, an advanced shaped charge warhead which incorporates wave shaping for increased performance. Recent work at MRL on shaped charges includes the jet-initiation and disruption of bare and covered Comp B and other explosives by Chick et al [2,3], the numerical modelling of the liner collapse and jet formation in the MRL 38 mm shaped charge by Smith [4] using the two-dimensional hydrodynamic finite difference code HELP, and the production of a one-dimensional code for shaped charge analysis by Jones [5]. As part of the continuing program on warhead research at MRL, it was decided to investigate the increase in performance which could be obtained in the MRL 38 mm shaped charge by the use of wave shaping.

The first mention of the application of wave shaping to shaped charges in the open literature is in the classic paper of Birkhoff, McDougall, Pugh and Taylor in 1948 [6]. They noticed that if the detonation wave had a conical shape, so that it reached all parts of the liner at the same time, then the expression for the velocity of the jet became:

$$V_j = V_o / \tan (\alpha/2), \quad (1)$$

where V_o is the velocity of the liner and α is the cone half angle (see Fig. 1). Equation (1) indicates that the velocity of the jet can be increased indefinitely simply by decreasing the cone angle, although there is a practical limitation in that both the mass and momentum of the jet tend to zero as α tends to zero. The paper by Birkhoff et al presents a steady-state theory and neglects the velocity gradient along the length of the jet; however it can be used to give a first estimate of the velocity of the jet-tip in the MRL 38 mm shaped charge if the detonation wave can be considered as formed into a conical shape. Using the steady-state theory of Birkhoff et al (which is also described in ref [7]) and the following experimental parameters

for the MRL shaped charge:

$$\begin{aligned}V_j(\text{tip}) &= 0.73 \text{ cm}/\mu\text{s}, \\U_D &= 0.798 \text{ cm}/\mu\text{s}, \\ \alpha &= 21^\circ,\end{aligned}$$

where U_D is the detonation velocity, the velocity of the liner is found to be

$$V_o = 0.234 \text{ cm}/\mu\text{s}.$$

When used in equation (1) this gives

$$V_j(\text{tip}) = 1.26 \text{ cm}/\mu\text{s},$$

which is a considerable improvement on the present experimental value of 0.73 cm/ μ s.

With the above considerations in mind, some preliminary work was done to investigate the effect of a nonplanar detonation wave on the collapse of the liner and the formation of the jet. Both spherically-diverging and spherically-converging detonation waves were considered and the analysis was performed using a modified form of the Pugh, Eichelberg and Rostoker theory [8] (hereafter known as the PER theory). It was thought that the spherically diverging wave (i.e. point-initiation) would have little effect on overall performance, while it was expected that the spherically-converging wave would approximate the conical collapse case. The method and results are described in Section 2. It can be seen that, as expected, the difference between a plane detonation wave and point-detonation is very slight, while the spherically-converging wave has a marked effect on the velocity-gradient within the jet. Neither of these results in any increase in $V_j(\text{tip})$ however, as in both cases the waves are effectively planar at the cone-apex.

At that stage it was decided to concentrate on a conical wave shape. Leaving aside for the moment the question of how such a wave might be produced, we decided to look at the increased performance obtainable from the MRL standard shaped charge assuming that a perfectly conical detonation wave was available to collapse the liner. We used two methods to look at this problem. In section 3a an analytical method based on the "one-dimensional code" approach is described. This calculation was simply an extension of some work done in a previous MRL report [5] on modelling the MRL shaped charge using a collection of analytical expressions for the various stages of liner-collapse and jet-formation. A simple computer code was written to evaluate these expressions and the conical wave collapse was simulated by setting the collapse angle β equal to the cone half angle α . This work resulted in a predicted $V_j(\text{tip})$ of 1.20 cm/ μ s, which is in remarkably good agreement with the value of 1.26 cm/ μ s obtained using the simple steady-state theory.

In section 3b the conical-wave-collapse of the liner was modelled using the two-dimensional finite difference hydrocode HELP. This predicted a $V_j(\text{tip})$ of 0.93 cm/ μ s, a value which is not in good agreement with the values predicted using either the 1D code or the steady-state theory. There are some problems associated with the use of HELP in modelling the MRL shaped charge however. Even for the case of a plane detonation wave, HELP predicts $V_j(\text{tip}) = 0.66$ cm/ μ s, whereas the experimental value is 0.73 cm/ μ s. In going from the plane wave to a conical wave, though, HELP does predict an increase from 0.66 cm/ μ s to 0.93 cm/ μ s, i.e. 43%, which is still a considerable improvement.

The results presented in Section 3 indicate that a considerable increase in jet tip velocity can be obtained by shaping the detonation wave into a conical form which impacts the liner at all points simultaneously. The increased jet-tip velocity will lead to greater stretching of the jet and hence to greater penetrating ability. This is not the complete story however. Early experiments on wave-shaping in the USA [9] indicated that increases in penetration depth of up to 30% could be obtained, but only at the expense of slightly reduced hole volumes. This is because the wave-control-inserts which actually shape the detonation front also disturb the pressure amplitude behind the front and lead to a reduced impulse on the liner surface. This will be discussed more fully in Section 4.

2. SPHERICAL WAVEFRONT RESULTS

To investigate the effect of either point-initiation or a spherically-converging wave front on jet characteristics, a modified form of the Pugh, Eichelberg and Rostoker theory was used [8]. The original PER theory modelled the collapse of a conical-shaped charge liner by a plane detonation wave moving parallel to the axis of the charge. The relevant equations are:

$$\delta = \sin^{-1} (V_o/2U) \quad (2)$$

$$V_j = \frac{V_o \cos(\alpha + \delta - \beta/2)}{\sin(\beta/2)} \quad (3)$$

$$\frac{m_j}{m} = \sin^2(\beta/2) \quad (4)$$

$$\tan \beta = \frac{\sin(\alpha+2\delta) - x \sin \alpha [1 - \tan \delta \tan(\alpha+\delta)] V_o'/V_o}{\cos(\alpha+2\delta) + x \sin \alpha [\tan(\alpha+\delta) + \tan \delta] V_o'/V_o} \quad (5)$$

where δ is the angle between the direction an element of the liner travels after being struck by the detonation wave and the normal to the surface of the liner, m_j is an element of jet mass, and x is the initial axial coordinate of the liner element. A prime denotes differentiation with respect to x . The velocity with which the detonation front sweeps along the liner surface is designated by U . For a plane detonation front and a conical liner $U = U_D / \cos \alpha$, where U_D is the detonation velocity of the explosive. Allison and Vitali [10] later modified these equations to apply to a spherical detonation wave emerging from an on-axis-point initiation, and more recently Behrmann [11] generalised them to apply to an arbitrary off-axis-point initiation with variable liner geometry.

The primary difference between the equations for a plane wave and those for either point-initiation or point-convergence (i.e. a spherically-converging detonation wave which converges to a point at a distance d from the apex of the cone) is that U is no longer constant but is given by

$$U = U_D / \cos \gamma \quad (6)$$

where γ is the minimum angle between the normal to the spherical wave front and the cone wall at the intersection of the detonation wave and the cone wall. Following the procedure established by PER the equation for β now becomes

$$\tan \beta = \frac{\tan \alpha + T' V_0 \cos A + x \tan \alpha (\delta' \tan A - V_0' / V_0)}{1 + x \tan \alpha [\delta' + (V_0' / V_0) \tan A] - T' V_0 \sin A} \quad (7)$$

where $\delta' = [V_0' / V_0 - U' / U] \tan \delta$, $A = \alpha + \delta$, and $T(x)$ is the time at which the detonation wave reaches a position x on the liner.

For a plane wave

$$\cos \gamma = \cos \alpha, \quad (8)$$

$$\frac{U'}{U} = 0, \quad (9)$$

$$T(x) = x / U_D \quad (10)$$

and equation (7) reduces to equation (5).

For point-detonation, equations (8-10) are replaced by

$$\cos \gamma = \frac{\cos \alpha (1 + x/d \cos^2 \alpha)}{\sqrt{1 + 2x/d + (x/d \cos \alpha)^2}}, \quad (11)$$

$$\frac{U'}{U} = \frac{d \cos^2 \alpha + x}{\sqrt{d^2 \cos^2 \alpha + 2dx \cos^2 \alpha + x^2}} - \frac{1}{x + d \cos^2 \alpha}, \quad (12)$$

and

$$T(x) = \frac{\sqrt{(x+d)^2 + (x \tan \alpha)^2}}{U_D} - \frac{d}{U_D} \quad (13)$$

where d is the distance between the point of initiation and the cone-apex, while for a spherically-converging detonation wave we have

$$\cos \gamma = \frac{\cos \alpha (1 - x/d \cos^2 \alpha)}{\sqrt{1 - 2x/d + (x/d \cos \alpha)^2}}, \quad (14)$$

$$\frac{U'}{U} = \frac{x - d \cos^2 \alpha}{d^2 \cos^2 \alpha - 2dx \cos^2 \alpha + x^2} - \frac{1}{x - d \cos^2 \alpha}, \quad (15)$$

and

$$T(x) = \frac{d}{U_D} - \frac{\sqrt{(x \tan \alpha)^2 + (d - x)^2}}{U_D} \quad (16)$$

where d is now the distance between the cone-apex and the point on the inside of the cone to which the wave converges.

In order to evaluate equation (7) we need to know the dependence of V_0 on x . As the purpose of the present calculation is merely to illustrate the relative effect of the different wave shapes we simply take a representative function of the form

$$V_0(x) = 0.43 - 0.001 x (1.0 + x) \quad (17)$$

Equation (17) generates approximately the correct shape and magnitude of the velocity gradient for most classical-shaped charges.

The velocity gradient within the jet for the point-initiated charge for $d = 2.0, 5.0$ and 10.0 cm and for the plane-wave case is shown in Fig. 2. Note that the velocity of the jet tip is independent of d , and that the effect of the curvature of the wave is not very large. This is a useful result to keep in mind when designing a 1D code for jet simulation.

For the spherically-converging wave the effect of the curvature is much more pronounced, as can be seen in Fig. 3. For finite values of d and at small x values, the jet does have a velocity greater than that of the plane wave case, indicating a type of "geometrical inverse-velocity-gradient effect", but the effect is so small that it would be swamped by other considerations. We note that Fig. 3 does suggest that a spherically-converging wave could be a useful starting point for the design of a jet with zero velocity gradient.

Equation (3) shows that the velocity of the jet-tip can be increased by decreasing β . In the case of a conical detonation front, this is taken to the extreme limit by taking $\beta = \alpha$. From the results just presented it seems evident that this is the most suitable shape for study. The next two sections examine the effect of this particular waveform using two different methods.

3. CONICAL DETONATION WAVE

3.1 Analytical Results

A simple model of the MRL 38 mm shaped charge has recently been described [5]. The model is based on the analytical work of Pugh, Eichelberg and Rostoker [8] and uses the modified Richter equation to calculate the liner bending angle δ , followed by the steady-state Taylor equation to calculate the initial liner speed V_0 . The inverse-velocity-gradient effect is included by allowing the liner to have a velocity-time curve of the type described by Carleone et al [12]. The two phenomenological constants K and ϕ_0 required for the modified Richter equation are found using data for the BRL 105 mm shaped charge, while the time constant τ required for liner acceleration is found by adjusting the velocity of the jet tip until it agrees with the experimental value. The model has been used to calculate the jet velocity-gradient and collapse-angle versus time for the MRL 38 mm shaped charge, and the results agree well with recent experimental data by Smith and Macintyre [4] and Chick [13].

Although the model assumes that the liner is collapsed by a plane detonation wave, a conical detonation-front can easily be modelled by setting the collapse angle β equal to the cone half angles α for the duration of the collapse. This results in a change in V_j (tip) from 0.73 cm/ μ s for plane wave initiation to 1.20 cm/ μ s for conical detonation. This agrees well with the value of 1.26 cm/ μ s obtained using the steady-state theory of Birkhoff et al. [6], although there is no reason why the two values should agree exactly. In fact the value of 1.20 cm/ μ s will be slightly inaccurate anyway as the constants K and ϕ_0 are known to vary with the angle of inclination of the detonation wave on the liner surface [17], and this has not been taken into account in the model calculation. Nevertheless, this gives an indication of the increased performance which can be expected, and more accurate estimates could be made using the model if the variation of K and ϕ_0 with the angle of inclination was included.

3.2 HELP Code Simulation

The 2D finite difference hydrodynamic code HELP has recently been used to model the MRL 38 mm shaped charge, and a full account of this work can be found in the report by Smith and Macintyre [4]. The calculation fairly accurately predicts the overall features of the collapse of the liner, the formation of the jet and slug, and the expansion of the aluminium casing, but there are nevertheless some unresolved anomalies relating to the exact shape of the jet tip and the back of the slug. The predicted jet-tip velocity of 0.66 cm/ μ s is also significantly lower than the best experimental estimate of 0.73 cm/ μ s. Other problems appear when the geometry of the liner is changed. For example, when the rounded-liner apex is replaced by a point, to simulate the geometry employed in the simple analytical model described in the previous section, then a physically inadmissible split develops along the length of the jet. The reason for this is that the massless tracer particles which define the boundary between the liner and the void are not accelerated sufficiently by the passage of the shock through the liner. The first tracer on the axis of the cone is left behind, thus allowing the split to develop. Surprisingly, the velocity of the remainder of the jet tip is not significantly disturbed by this fault.

HELP can be used to model shaped-charge-collapse by a conical detonation wave simply by ensuring simultaneous detonation of each of the explosive cells adjacent to the copper liner. This technique was used by Smith on the MRL 38 mm shaped charge with the correct rounded apex, but again a physically inadmissible split appeared along the length of the jet due to the very small acceleration of the tracer particle on the axis of the cone. The velocity of the remainder of the jet tip was 0.93 cm/ μ s, which represents an increase of approximately 40% over the value predicted when a plane detonation wave is used. This trend is not in disagreement with the approximately 64% increase predicted by the analytical model, as presumably a value higher than 0.93 cm/ μ s would be predicted by HELP if the numerical problems did not occur.

Before concluding this section it is noted that the problems occurring in the HELP code near the jet tip are nontrivial and do not appear to be easily solved. It is felt that the real problem lies with the manner

in which the massless tracer particles defining the interfaces are moved. In HELP, each tracer particle is surrounded by a fictitious cell, and the velocity of the tracer is taken to be a weighted average of the velocities in each of the (real) neighbouring cells, with the weighting factor being related to the volume of each neighbouring cell overlapped by the fictitious cell. In a typical HELP run the thickness of the liner at the apex of the cone may be only five or six cells thick and the velocity gradient is very high. Under these conditions the weighting scheme just described may allow a correlation between the tracer particles either side of the thin copper liner, with the result that the tracers describing the jet tip are slowed down by the more massive slug, while the velocity at the back of the slug is increased because of the correlation with the jet tip. It is interesting to note that similar effects can be seen in the EPHULL simulation of the MRL 38 mm shaped charge (Cullis [13]).

4. DISCUSSION

The increase in jet-tip velocity predicted in the previous section will lead to a more rapid lengthening of the jet in flight and hence to increased depth of penetration for a given standoff distance. (Note that this will also lead to a decrease in jet diameter.) Whether or not this also leads to an increased hole volume depends on how the conical wave shape has been formed. Early experimental attempts using peripheral-initiation showed that penetration could be increased by up to 20% using this technique, but that hole volumes were reduced by one third or more. This early work was reported by Cook [9], Sultanoff [15], and Cook et al. [16]. The decrease in hole volume is caused by the disruption of the detonation-head. This is a high pressure region behind the detonation front which has an approximate cone-shape with a diameter slightly less than the diameter of the shaped charge. The exact shape is determined by the rarefaction waves from the sides of the charge and is fully developed when the detonation front has travelled about 2-1/2 to 3 charge diameters [9]. It is this region which is important for shaped charge performance. In order to shape the detonation wave without disturbing the detonation head, Cook et al. [16] performed a series of experiments in which the wave was shaped by a variety of inert metal fillers. Best results were found with fillers having a cone shape with a height equal to half the diameter of the shaped charge. These configurations achieved considerable increases in penetration with no reduction in hole volume (in some cases hole volume was slightly increased), and the results were in good agreement with the predictions of the detonation-head theory.

The above discussion illustrates the need for further work before a design for a wave shaping insert for the MRL 38 mm shaped charge can be attempted. A more extensive survey of early experimental work on wave shaping should be made and the results interpreted in terms of the detonation-head theory. The problems with the HELP and EPHULL codes need to be resolved and then extensive computer runs made to determine the optimum shape and material for the wave-control insert. The code chosen for this study should also contain a true explosive-burn routine so that critical diameter and other effects can be modelled.

5. ACKNOWLEDGEMENTS

I would like to thank Mr F.G.J. May for suggesting this area of work, and also for participating in many helpful discussions on the behaviour of shaped charges. I also wish to thank Mr D.L. Smith for providing the HELP code results which were discussed in Section 3.2.

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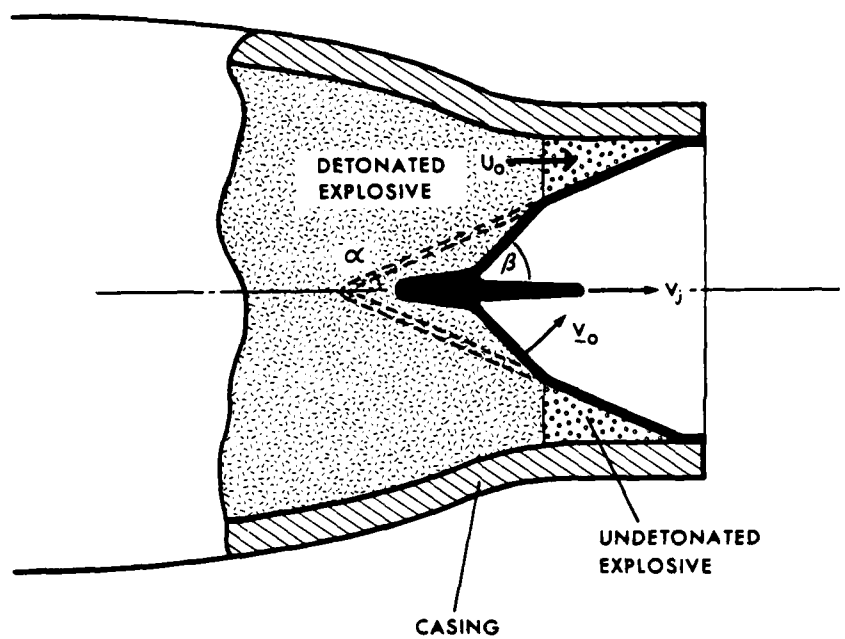


FIGURE 1 Illustration of collapsing liner and formation of jet and slug. The original cone half angle is α , the collapse angle β . v_o is the velocity of the collapsing liner.

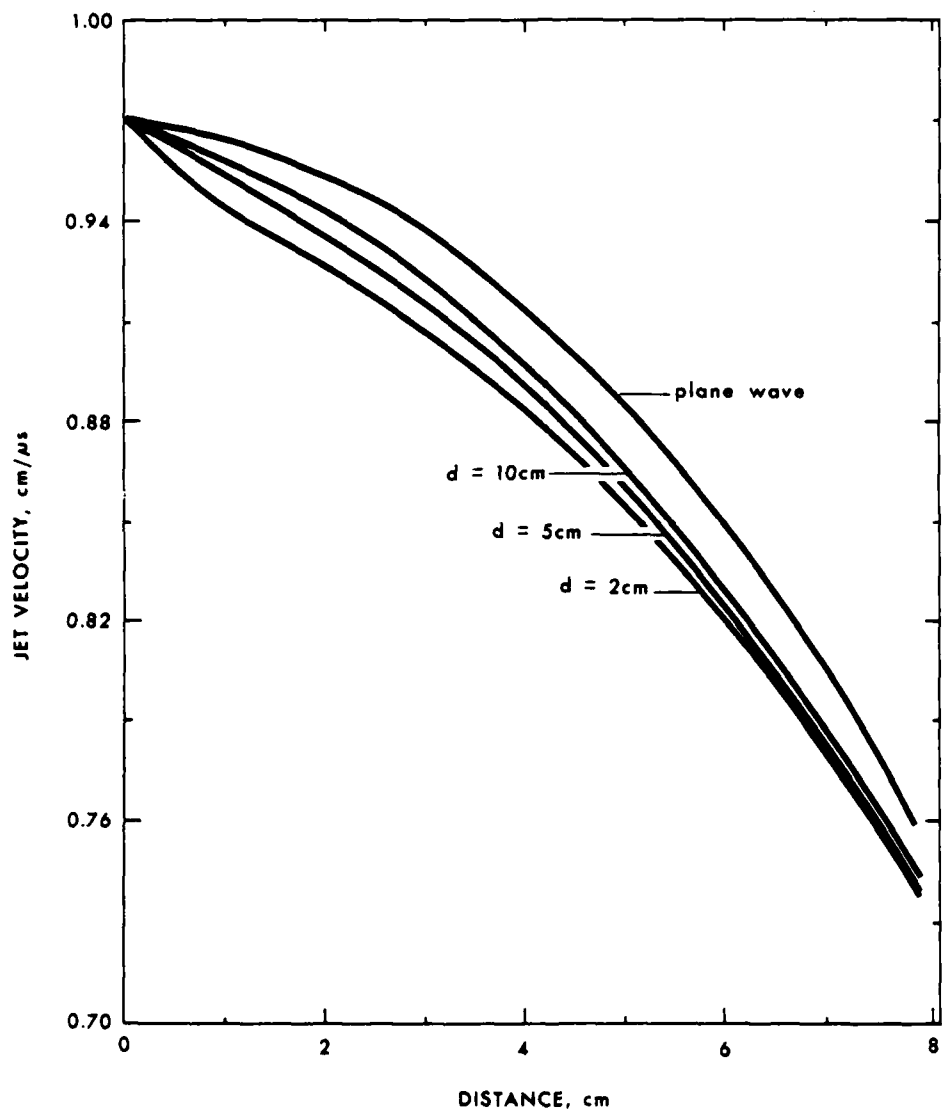


FIGURE 2 Spherically diverging wave. d is the distance, in cm, between the point of initiation and the apex of the cone.

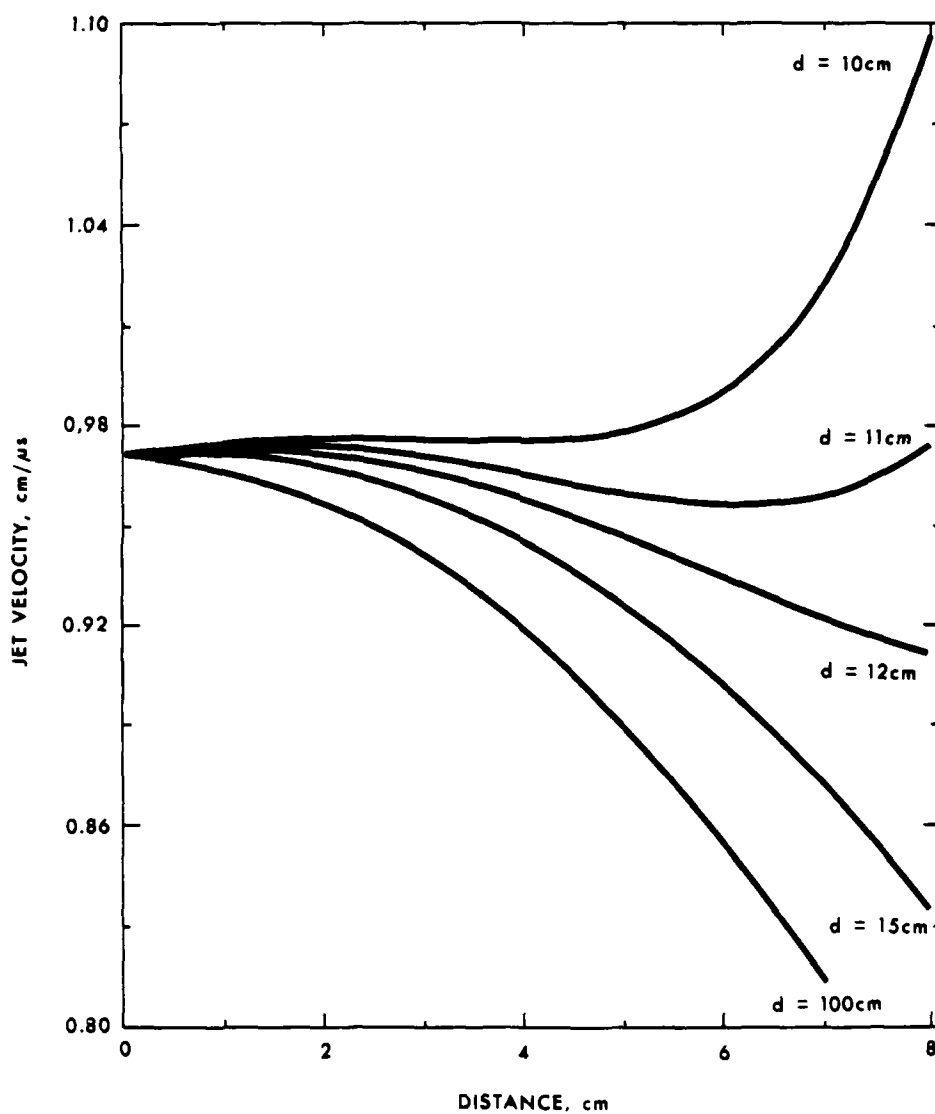


FIGURE 3 Spherically converging wave. Here d represents the distance, in cm, between the apex of the cone and the point to which the wave converges.

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